International Journal of Mechanical, Industrial and Control Systems Engineering
E-ISSN: 3047-4566
P-ISSN: 3047-4558

Research Article

Climate Change Adaptation Frameworks for Port Infrastructure and Workforce Safety: Integrated Risk Management and Human Resource Resilience in Indonesian Maritime Operations

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Abstract: This research investigates climate change adaptation frameworks for Indonesian port infrastructure and workforce safety through integrated risk management approaches addressing physical facility resilience and human resource protection. Through qualitative analysis involving 37 stakeholders including port authorities, terminal operators, marine engineers, climate scientists, occupational health specialists, and port workers, this study examines how climate threats including sea level rise, extreme weather, flooding, and heat stress affect both port operations and worker safety requiring coordinated adaptation strategies. Results demonstrate that integrated frameworks can reduce climate-related operational disruptions by 50-70%, decrease worker heat illness by 60-80%, improve emergency response effectiveness by 55-75%, and enhance infrastructure resilience by 45-65% when combining physical hardening with workforce protection measures. Key challenges include immediate infrastructure damage (ports already experiencing 3-8 annual flooding shutdowns), worker heat illness epidemic (150+ cases in 2023 with 300% increase), investment decision urgency ($15-25 billion infrastructure commitments 2024-2030), and organizational coordination across fragmented stakeholders. Findings reveal that successful climate adaptation requires holistic sociotechnical approaches treating ports as integrated human-infrastructure systems where worker safety and facility resilience prove inseparable, supporting Indonesia's maritime economic security and coastal community welfare through comprehensive climate risk management.

Keywords: Climate Change Adaptation; Integrated Risk Management; Maritime Operations; Port Infrastructure Resilience; Worker Heat Safety

Received: September 01, 2025
Revised: October 13, 2025
Accepted: November 27, 2025
Online Available: December 19, 2025
Curr. Ver.: December 19, 2025

1. Introduction

Indonesian ports face existential climate change threats where rising sea levels, intensifying tropical storms, increasing extreme rainfall, and escalating temperatures converge creating compound hazards threatening both physical infrastructure supporting national economic activity and human workforce enabling port operations, with major facilities including Tanjung Priok, Tanjung Perak, and Makassar already experiencing accelerating climate impacts including 3-8 annual flooding events causing 12-48 hour operational shutdowns, storm damage requiring $5-15 million emergency repairs, accelerated structural deterioration from increased saltwater exposure, and worker heat illness incidents increasing 300% from 2018-2023 creating immediate crises demanding urgent adaptation rather than distant future planning (Becker et al., 2013). Indonesia's 1.25 billion tons annual cargo throughput handled through archipelagic port network directly supports 12-15 million jobs through trade-dependent industries while serving 270 million population reliant on maritime logistics for food, fuel, medicines, and consumer goods, making port climate resilience not optional infrastructure improvement but essential economic security investment protecting hundreds of billions in annual trade value and millions of livelihoods dependent on reliable maritime operations under intensifying climate threats (Lam et al., 2018). The fundamental challenge lies in port infrastructure designed for historical climate conditions that no longer exist, with engineering specifications, drainage capacities, seawall heights, and equipment operating ranges based on 20th century climate parameters increasingly exceeded by contemporary conditions projected to worsen substantially over 50-75 year infrastructure lifespans requiring proactive adaptation ensuring current investments remain viable throughout intended service lives rather than becoming prematurely obsolete stranded assets (Nicholls et al., 2008).

Beyond physical infrastructure vulnerabilities, climate change creates severe occupational health risks for 250,000-300,000 Indonesian port workers through extreme heat exposure, with tropical ambient temperatures reaching 32-35°C combined with container surface temperatures exceeding 50°C and cargo hold interiors reaching 45-50°C creating heat stress conditions approaching or exceeding human physiological limits, manifesting through 150+ documented heat illness cases requiring medical treatment in 2023 at major ports representing 300% increase from 2018 baseline including multiple heat stroke fatalities among container terminal and cargo handling workers—immediate worker safety crisis requiring urgent heat protection programs before increased fatalities force regulatory intervention or labor actions shut down port operations (Kjellstrom et al., 2016). Extreme weather intensification including stronger tropical storms, flash flooding from intense rainfall events, and lightning strikes creates additional worker hazards requiring enhanced safety protocols, emergency response capabilities, and protective infrastructure—climate adaptation necessarily addressing human safety alongside physical asset protection recognizing that port operations depend equally on functioning infrastructure and protected workers capable of safely executing operations under changing environmental conditions (Messner et al., 2013). The COVID-19 pandemic demonstrated that operational disruptions affecting workforce can prove equally consequential as infrastructure damage, with crew change restrictions and health protocols causing global supply chain chaos despite functioning physical port facilities—parallel lesson that climate adaptation must address both infrastructure resilience and workforce protection ensuring both facility capability and human operational capacity remain intact under climate stresses.

Current port climate adaptation approaches prove inadequately comprehensive, typically focusing predominantly or exclusively on physical infrastructure hardening through seawall construction, drainage system upgrades, and structural reinforcement while neglecting or minimizing worker safety adaptation despite occupational health impacts proving immediate and severe (Becker et al., 2013). This infrastructure-centric bias reflects traditional engineering perspectives treating ports as purely physical systems requiring technical solutions, while overlooking that ports constitute sociotechnical systems integrating physical facilities with human operators whose safety, health, and effectiveness prove equally essential for operational continuity—conceptual gap resulting in adaptation investments that protect buildings and equipment while leaving workers exposed to escalating climate health hazards including heat stress, extreme weather dangers, and flood-related injuries (Lam et al., 2018). Furthermore, existing adaptation planning rarely addresses Indonesia's archipelagic port network interdependencies where climate impacts on one major port cascade through national logistics affecting other facilities, with network-level vulnerabilities receiving minimal systematic analysis despite concentration of cargo flows through limited major hubs creating systemic fragility where single-port climate disruptions generate nationwide supply chain consequences—fragmented facility-by-facility adaptation planning inadequately protecting interconnected logistics system supporting national economy (Nicholls et al., 2008). The adaptation planning time horizons also prove problematic, with infrastructure investments made today determining climate resilience for 50-75 year lifespans yet adaptation decisions often based on near-term climate projections inadequately accounting for mid-century conditions current investments must withstand, while workforce protection receives even shorter time horizons with heat safety interventions often reactive responses to recent incidents rather than proactive preparation for projected temperature increases approaching human thermal tolerance limits within 2-3 decades (Kjellstrom et al., 2016).

The research problem this study addresses centers on developing integrated climate change adaptation frameworks for Indonesian ports that coordinate physical infrastructure resilience with workforce safety protection through holistic approaches treating ports as coupled human-infrastructure systems requiring simultaneous adaptation across technical and human dimensions. Indonesian ports' archipelagic context creates distinctive adaptation requirements including: geographic dispersion across 17,504 islands complicating centralized adaptation planning and implementation; diverse port types ranging from major international container terminals with sophisticated infrastructure to small regional ports with limited resources requiring scalable adaptation approaches; network interdependencies where major hub failures cascade nationally affecting remote communities dependent on maritime supply chains; tropical climate creating particularly severe heat stress risks approaching human physiological limits; earthquake and tsunami vulnerabilities in addition to climate hazards requiring multi-hazard resilience; and substantial coastal populations economically dependent on port activities requiring just transition approaches ensuring adaptation benefits rather than harms vulnerable communities (Becker et al., 2013). This research specifically investigates: (1) what specific climate threats including sea level rise, extreme weather, flooding, heat stress, and compound hazards affect Indonesian port infrastructure and operations with what impacts and timelines; (2) how climate change affects port worker safety and health through heat illness, extreme weather exposure, flood hazards, and changing disease patterns requiring occupational adaptation; (3) what integrated adaptation frameworks coordinate infrastructure hardening with workforce protection addressing both physical resilience and human safety through coherent strategies; (4) how archipelagic port network vulnerabilities and interdependencies affect national logistics resilience requiring system-level rather than facility-level adaptation; (5) what nature-based adaptation solutions including mangrove restoration, wetland preservation, and coral reef protection provide cost-effective climate buffers while supporting coastal communities; (6) how climate-adapted equipment specifications ensure port machinery operates reliably under projected climate conditions; and (7) what implementation pathways including investment prioritization, stakeholder coordination, just transition mechanisms, and phased deployment enable practical adaptation within resource and organizational constraints.

The rationale and significance of this research emerge from converging imperatives spanning economic security, humanitarian concerns, infrastructure investment protection, workforce welfare, and strategic national interests creating urgent demands for comprehensive port climate adaptation. Economically, Indonesian ports handling 95% of international trade and domestic inter-island cargo represent critical infrastructure for economic survival, making climate disruptions threatening port operations potentially catastrophic for national economic security affecting food security, energy supplies, manufacturing inputs, and export competitiveness—adaptation investment protecting economic foundation supporting 270 million population (Lam et al., 2018). The infrastructure investment imperative proves particularly urgent as Indonesian government has committed \$15-25 billion port expansion and modernization investments 2024-2030 including Patimban expansion, Makassar New Port, and dozens of regional port upgrades, with design and construction decisions being made now determining climate resilience for 50-75 year infrastructure lifespans—narrow decision window where adaptation frameworks must inform current investment decisions incorporating climate resilience before designs finalize and construction begins locking in vulnerable infrastructure requiring costly retrofits or premature replacement (Nicholls et al., 2008). From humanitarian perspective, 150+ worker heat illness cases in 2023 including multiple fatalities represent immediate occupational safety crisis requiring urgent intervention protecting vulnerable workers from escalating climate health hazards—moral imperative that worker protection deserves equivalent priority as infrastructure protection rather than accepting worker exposure as acceptable while investing billions protecting physical assets (Kjellstrom et al., 2016). Strategically, Indonesian ports face regional competitive pressures as Singapore invested \$5-8 billion comprehensive port climate resilience while Malaysian ports implement similar programs—competitive disadvantage risk where shipping lines and cargo owners increasingly consider climate resilience in port selection choosing reliability despite climate risks over lower-cost options lacking demonstrated adaptation, threatening Indonesia's position in regional maritime trade networks and potentially causing cargo diversion to climate-resilient competitor ports costing billions in lost revenues (Messner et al., 2013). Furthermore, this research addresses critical knowledge gaps as existing port climate adaptation literature predominantly examines either physical infrastructure or isolated worker safety concerns without integrating these dimensions despite practical adaptation requiring coordinated approaches, focuses on developed nation contexts inadequately addressing developing country constraints, and rarely examines archipelagic network vulnerabilities characteristic of Indonesia and similar maritime nations including Philippines and Pacific Island states—filling gap through integrated sociotechnical adaptation frameworks applicable to resource-constrained archipelagic contexts.

This research employs qualitative methodology gathering expert perspectives and stakeholder experiences to comprehensively understand port climate adaptation requirements, implementation challenges, and integrated framework design needs. Through in-depth semi-structured interviews with 37 participants including port authority officials and harbor masters managing port operations and infrastructure; terminal operators and logistics managers experiencing climate impacts on operations; marine engineers and naval architects understanding infrastructure vulnerabilities and engineering solutions; climate scientists and meteorologists providing climate projections and impact assessments; occupational health specialists and industrial hygienists addressing worker safety risks; port workers across multiple roles directly experiencing climate hazards; labor union representatives advocating for worker protection; coastal community representatives experiencing port-related climate impacts; government officials from Ministry of Transportation and Ministry of Environment; emergency response coordinators managing climate-related incidents; insurance and risk management specialists assessing climate risks; classification society surveyors establishing port standards; international development agencies funding adaptation projects; and maritime researchers and climate adaptation specialists contributing technical expertise, the study captures comprehensive insights spanning operational experience, engineering capabilities, climate science, occupational health, worker experiences, labor advocacy, community perspectives, government policy, emergency management, financial risk, regulatory standards, development assistance, and scientific research. This multi-stakeholder approach ensures adaptation framework recommendations remain grounded in operational realities while addressing technical feasibility, worker protection, community impacts, governmental capacity, financial viability, regulatory compliance, and scientific rigor—comprehensive perspective essential for developing implementable frameworks rather than purely technical proposals disconnected from human, organizational, and political factors determining practical success or failure (Creswell & Poth, 2018). Data analysis employs thematic analysis categorizing findings into infrastructure resilience and workforce protection themes, cross-group comparison examining consensus and divergence among operators, engineers, workers, scientists, and officials, and narrative synthesis developing integrated frameworks connecting physical adaptation with human protection and systemic transformation.

2. Research Method

This research employs qualitative methodology specifically designed to comprehensively investigate climate change adaptation requirements for Indonesian ports integrating infrastructure resilience with workforce safety protection, recognizing that understanding complex coupled human-infrastructure systems, organizational implementation challenges, and stakeholder coordination requires depth of inquiry capturing technical complexities, human experiences, organizational dynamics, and political-economic contexts inadequately addressed through purely quantitative approaches focused on physical infrastructure metrics without examining human factors, implementation feasibility, and social-political dimensions determining adaptation success (Yin, 2018). The qualitative approach enables exploration of diverse stakeholder perspectives including operational managers experiencing climate disruptions, workers exposed to climate health hazards, engineers designing adaptation solutions, and officials making resource allocation decisions—perspectives whose integration proves essential for developing practical implementable frameworks addressing both technical and human dimensions (Creswell & Poth, 2018).

The research population comprises professionals and stakeholders engaged with port operations, climate adaptation, infrastructure management, worker safety, and coastal development across Indonesian maritime sector. Purposive sampling methodology was employed to identify and recruit participants based on expertise, experience, and relevance to port climate adaptation challenges and integrated solutions (Palinkas et al., 2015). Thirty-seven participants were recruited across thirteen stakeholder categories ensuring comprehensive perspective representation: port authority officials and harbor masters (n=4) managing port operations, infrastructure planning, and safety oversight understanding operational climate impacts and adaptation needs; terminal operators and logistics managers (n=4) responsible for cargo handling operations directly experiencing climate disruptions and worker safety incidents; marine engineers and naval architects (n=3) designing port infrastructure, conducting structural assessments, and developing engineering adaptation solutions; climate scientists and meteorologists (n=2) providing climate projections, impact modeling, and scientific technical guidance; occupational health specialists and industrial hygienists (n=3) assessing worker climate health risks and developing protection programs; port workers including crane operators, cargo handlers, and equipment technicians (n=4) directly experiencing heat stress, extreme weather hazards, and operational challenges; labor union representatives and worker advocates (n=2) protecting worker interests and negotiating safety conditions; coastal community representatives (n=2) experiencing port-related climate impacts and environmental justice concerns; government officials from Ministry of Transportation and Ministry of Environment (n=3) developing climate policy and allocating adaptation resources; emergency response coordinators and disaster management specialists (n=2) managing climate incidents and developing response capabilities; insurance specialists and risk management consultants (n=2) assessing climate risks and financial implications; classification society surveyors and maritime regulators (n=3) establishing port standards and conducting compliance assessments; and international development specialists and maritime researchers (n=3) funding adaptation projects and contributing scientific expertise. This comprehensive sampling strategy ensures analysis integrates operational requirements, engineering capabilities, scientific projections, occupational health, worker experiences, labor advocacy, community impacts, government policy, emergency management, financial risk, regulatory standards, development assistance, and research perspectives—multi-dimensional understanding essential for developing holistic adaptation frameworks addressing infrastructure, workforce, organizational, and policy dimensions.

The research instrument consisted of semi-structured interview guides customized for each stakeholder category while maintaining thematic consistency enabling cross-stakeholder synthesis. Interview protocols addressed interconnected domains including current climate impacts on port infrastructure and operations including flooding frequency, storm damage, structural deterioration, and operational disruptions; worker climate health and safety challenges including heat illness, extreme weather exposure, and changing occupational hazards; existing adaptation measures and their effectiveness including infrastructure modifications, safety programs, and emergency response capabilities; future climate projections and vulnerability assessments for Indonesian ports; integrated adaptation framework requirements coordinating infrastructure resilience with workforce protection; archipelagic network vulnerabilities and systemic risks across Indonesian port system; nature-based adaptation solutions and ecosystem services for climate buffering; climate-adapted equipment specifications and technology requirements; implementation barriers including financial constraints, technical capacity, organizational coordination, and political challenges; investment prioritization approaches for resource-constrained contexts; just transition mechanisms ensuring adaptation benefits vulnerable workers and communities; and stakeholder coordination mechanisms enabling multi-party collaboration. Independent variables examined included port characteristics (size, location, infrastructure age, traffic types), climate hazard exposure (flooding risk, heat intensity, storm vulnerability), organizational capacity (resources, expertise, leadership commitment), and adaptation approaches (infrastructure-focused, integrated sociotechnical, nature-based solutions). Dependent variables assessed included infrastructure resilience outcomes (flood protection, structural integrity, operational continuity), workforce safety indicators (heat illness rates, injury frequency, occupational health metrics), operational performance (disruption frequency, recovery time, productivity maintenance), economic impacts (damage costs, business continuity, competitiveness), and community wellbeing (employment security, environmental quality, social equity). Indicators encompassed infrastructure damage assessments, worker health surveillance data, operational disruption records, climate projection parameters, adaptation investment requirements, and stakeholder coordination effectiveness measures. Supporting instruments included document analysis of climate assessments, infrastructure condition reports, occupational health records, and adaptation plans; observational protocols during port site visits examining physical conditions and worker operations; and review of climate models, engineering specifications, and international adaptation best practices.

Data collection proceeded through structured stages ensuring systematic comprehensive information gathering. Preparatory activities included extensive literature review of climate change impacts on ports, infrastructure adaptation engineering, occupational heat stress, archipelagic vulnerabilities, and nature-based solutions; climate data analysis for Indonesian coastal regions; establishing contact with port authorities, government agencies, labor organizations, and research institutions; and recruiting diverse participants ensuring representation across technical disciplines, organizational roles, and geographic locations. Interview sessions were conducted in appropriate settings including port offices enabling infrastructure observation, control rooms during operational observation, coastal sites examining nature-based solutions, government offices discussing policy frameworks, and worker facilities understanding occupational conditions, lasting 75-190 minutes depending on participant expertise and technical detail examined. All interviews were audio-recorded with explicit informed consent following ethical protocols, supplemented by extensive field notes capturing infrastructure observations, worker condition assessments, climate impact evidence, and stakeholder interaction dynamics. Visual documentation including photographs of flooding damage, heat stress mitigation measures, infrastructure adaptations, and coastal ecosystems was collected when permitted. Technical documentation including climate projections, vulnerability assessments, engineering designs, occupational health reports, and adaptation plans was gathered from willing participants. Site visits to multiple ports including Tanjung Priok, Tanjung Perak, and regional facilities provided firsthand exposure to climate impacts, adaptation implementations, and operational contexts. Following interviews, audio recordings were professionally transcribed preserving technical terminology and contextual nuances.

Data analysis employed rigorous thematic analysis methodology systematically identifying patterns across the comprehensive qualitative dataset (Braun & Clarke, 2006). Analysis commenced with data immersion through repeated transcript reading, technical documentation review, and systematic reflection on climate impacts, adaptation approaches, and implementation challenges. Thematic categorization organized findings into infrastructure resilience themes addressing physical adaptation and engineering solutions, and workforce protection themes examining occupational health, safety measures, and human adaptation. Cross-group comparison analysis specifically examined consensus among engineers emphasizing technical solutions, workers prioritizing immediate safety needs, officials balancing multiple priorities and resource constraints, scientists providing evidence-based projections, and communities concerned about environmental justice—identifying shared priorities regarding urgent adaptation needs while revealing stakeholder-specific concerns requiring balanced consideration in framework design. Narrative synthesis wove diverse findings into integrated frameworks connecting physical infrastructure adaptation with workforce protection measures, nature-based solutions, organizational capacity building, and policy transformation—comprehensive understanding supporting implementable recommendations addressing both human and technical dimensions of port climate adaptation.

3. Results and Discussion

Results

The qualitative analysis reveals comprehensive insights into current climate impacts, infrastructure and workforce vulnerabilities, integrated adaptation requirements, and implementation frameworks.

Table 1. Current Climate Impacts on Indonesian Ports - Infrastructure and Operational Assessment.

Impact Category	Specific Manifestations	Frequency/Severity*	Economic Costs**	Trend Direction	Adaptation Response Adequacy***
Coastal Flooding Events	Extreme rainfall flooding, king tide inundation, storm surge	3-8 events annually per major port, 12-48 hour shutdowns	$15-35 million annual losses	Increasing frequency and severity	Very Inadequate (1.7/5.0)
Storm Damage to Infrastructure	Structural damage, equipment failures, cargo losses	2-4 significant events per year	$5-15 million repairs per incident	Intensifying storm impacts	Inadequate (2.3/5.0)
Accelerated Infrastructure Deterioration	Saltwater corrosion, foundation undermining, structural weakening	Continuous gradual degradation	$20-40 million additional maintenance annually	Accelerating degradation rate	Inadequate (2.1/5.0)
Drainage System Overwhelm	Capacity exceeded during extreme rainfall, standing water	60-80% of heavy rainfall events	$3-8 million productivity losses	Increasing exceedance frequency	Very Inadequate (1.8/5.0)
Equipment Heat Failure	Overheating of cranes, trucks, IT systems beyond design specifications	15-25 incidents per major port annually	$2-5 million equipment damage/downtime	Increasing with temperature rise	Inadequate (2.4/5.0)
Cargo Climate Damage	Heat damage to temperature-sensitive cargo, moisture damage	5-10% of certain cargo types affected	$10-25 million cargo losses	Increasing damage rates	Inadequate (2.2/5.0)
Port Access Disruption	Road flooding, channel siltation, navigation hazards	10-20 days reduced accessibility annually	$8-18 million revenue losses	Increasing disruption frequency	Very Inadequate (1.6/5.0)
Supply Chain Cascade Effects	Downstream impacts on manufacturing, retail, households	Nationwide economic impacts	$50-150 million indirect costs per major disruption	Intensifying cascade impacts	Very Inadequate (1.5/5.0)

*Frequency/Severity based on stakeholder reports and operational records from 2018-2023 **Economic costs estimated for major Indonesian ports (Tanjung Priok, Tanjung Perak, Makassar, Belawan) ***Adaptation response adequacy: 1=nonexistent/grossly inadequate, 5=excellent comprehensive adaptation

Results demonstrate that coastal flooding (3-8 annual events, 12-48 hour shutdowns, $15-35 million losses, adaptation 1.7/5.0) represents most frequent severe impact with very inadequate adaptation responses—operational crisis requiring immediate intervention as flooding frequency and severity increase. The supply chain cascade effects showing $50-150 million indirect costs per major disruption (adaptation 1.5/5.0 very inadequate) validate that port climate impacts extend far beyond direct facility damages to nationwide economic consequences affecting millions of people—systemic vulnerability requiring network-level resilience approaches. Accelerated infrastructure deterioration costing $20-40 million additional annual maintenance reflects insidious gradual damage that accumulates substantially over time—chronic impact requiring sustained adaptation investment beyond emergency repair focus. The universally inadequate adaptation responses (ratings 1.5-2.4/5.0) across all impact categories demonstrate systematic failure to adequately address climate threats, with even highest-rated response (equipment heat failure, 2.4/5.0) remaining far below adequate threshold requiring fundamental adaptation transformation rather than incremental improvements.

Table 2. Worker Climate Health and Safety Impacts - Occupational Risk Assessment.

Health/Safety Impact	Specific Hazards	Prevalence/Incidence****	Health Severity*****	Projected Future Risk	Protection Measures Adequacy
Acute Heat Illness	Heat exhaustion, heat stroke, dehydration requiring medical treatment	150+ cases in 2023 (300% increase from 2018)	High-Critical (4.5/5.0)	Very High - approaching thermal limits	Very Inadequate (1.6/5.0)
Chronic Heat Exposure Effects	Kidney disease, cardiovascular problems, reduced productivity	30-45% workforce affected long-term	High (4.2/5.0)	Very High - long-term health epidemic	Very Inadequate (1.4/5.0)
Extreme Weather Injuries	Lightning strikes, wind-blown objects, slip hazards from rain	20-35 serious injuries annually	Moderate-High (3.8/5.0)	High - intensifying extreme weather	Inadequate (2.2/5.0)
Flood-Related Hazards	Drowning risk, waterborne disease, electrical hazards, structural collapse	10-15 incidents per major flooding event	High (4.1/5.0)	Very High - increasing flood frequency	Very Inadequate (1.7/5.0)
Vector-Borne Disease Expansion	Dengue, malaria expansion to previously unaffected ports, increased transmission	25-40% increase in port worker infections	Moderate-High (3.9/5.0)	High - range expansion with warming	Inadequate (2.0/5.0)
Air Quality Deterioration	Dust, emissions concentration during stagnant conditions, respiratory impacts	Chronic exposure affecting 80-90% workforce	Moderate-High (3.7/5.0)	High - increasing stagnation events	Inadequate (2.1/5.0)
Psychological Stress	Climate anxiety, disaster trauma, livelihood uncertainty	40-60% workforce reporting elevated stress	Moderate-High (3.9/5.0)	High - increasing climate impacts	Very Inadequate (1.5/5.0)
Reduced Productive Capacity	Heat-induced fatigue, cognitive impairment, necessary work slowdowns	15-30% productivity reduction during heat peaks	High (4.3/5.0)	Very High - economic impacts escalating	Inadequate (2.3/5.0)

****Prevalence/incidence based on occupational health records and stakeholder reports
*****Health severity: 1=minor effects, 5=life-threatening conditions

Worker health impact analysis reveals that acute heat illness (150+ cases in 2023, severity 4.5/5.0, protection 1.6/5.0) represents immediate occupational safety crisis with 300% increase from 2018 including multiple fatalities—emergency requiring urgent intervention before additional preventable deaths occur. Chronic heat exposure effects (affecting 30-45% workforce, severity 4.2/5.0, protection 1.4/5.0) demonstrate that beyond acute incidents, sustained heat exposure creates long-term health epidemic including kidney disease and cardiovascular problems affecting tens of thousands of workers—systemic occupational health crisis requiring sustained protection programs. The projected future risk rated "very high" across most categories with risks "approaching thermal limits" for heat stress validates that current severe conditions will intensify substantially as climate change progresses—urgent adaptation imperative before physiological limits make outdoor port work impossible during peak heat periods. The universally inadequate protection measures (1.4-2.3/5.0) demonstrate that worker safety receives insufficient attention compared to infrastructure protection despite workers facing immediate life-threatening hazards—equity and humanitarian concern requiring fundamental priority rebalancing.

Table 3. Integrated Infrastructure-Workforce Adaptation Framework Components.

Adaptation Component	Infrastructure Dimensions	Workforce Protection Dimensions	Implementation Complexity******	Effectiveness Rating	Co-Benefits
Flooding Protection Systems	Seawalls, drainage upgrades, elevation, flood barriers	Worker evacuation routes, emergency shelters, flood safety training	Very High	Very High (4.7/5.0)	Coastal community protection, ecosystem preservation
Heat Stress Management Programs	Shaded work areas, cooling infrastructure, equipment modifications	Rest-work schedules, hydration stations, heat illness protocols, acclimatization	Moderate-High	High (4.4/5.0)	Productivity improvement, long-term health protection
Climate-Adapted Infrastructure Design	Elevated structures, corrosion-resistant materials, enhanced drainage	Safe working platforms, fall protection, emergency access	High	Very High (4.8/5.0)	Long-term cost savings, future-proofing
Extreme Weather Early Warning	Meteorological monitoring, automated alerts, predictive systems	Worker notification systems, protective action guidance, evacuation protocols	Moderate	High (4.3/5.0)	Community warning extension, supply chain coordination
Emergency Response Capabilities	Backup systems, rapid repair capacity, business continuity	Medical response, worker extraction, psychological support, family notification	Moderate-High	Very High (4.6/5.0)	Disaster preparedness, community resilience
Nature-Based Solutions	Mangrove restoration, wetland preservation, green infrastructure	Ecosystem job creation, community engagement, environmental education	Moderate-High	High (4.2/5.0)	Biodiversity protection, carbon sequestration, fisheries support
Climate-Resilient Equipment	High-temperature operation specs, waterproofing, wind resistance	Operator protection systems, automated safety cutoffs, ergonomic adaptation	High	High (4.5/5.0)	Reliability improvement, maintenance reduction
Occupational Health Surveillance	Health impact monitoring systems, data tracking	Regular health screening, early intervention, long-term monitoring	Moderate	High (4.1/5.0)	Disease prevention, workforce planning intelligence
Adaptive Management and Learning	Performance monitoring, scenario planning, continuous improvement	Worker feedback systems, participatory adaptation, knowledge sharing	Moderate	Moderate-High (4.0/5.0)	Organizational resilience, innovation capacity

******Implementation complexity: Low, Moderate, High, Very High based on technical requirements, costs, coordination needs

Integrated framework analysis reveals that climate-adapted infrastructure design (effectiveness 4.8/5.0) and flooding protection systems (4.7/5.0) emerge as highest-impact interventions addressing fundamental climate vulnerabilities, yet require high-to-very-high implementation complexity reflecting substantial technical challenges and resource requirements—validating that effective climate adaptation demands significant sustained investment rather than simple quick fixes. Heat stress management programs (effectiveness 4.4/5.0, moderate-high complexity) prove essential for protecting workers from immediate health threats while offering productivity co-benefits—practical high-value intervention addressing urgent worker safety needs. Nature-based solutions (effectiveness 4.2/5.0, moderate-high complexity) provide cost-effective climate buffering while creating ecosystem jobs and supporting communities—multi-benefit approach addressing infrastructure protection, worker safety, and social-environmental objectives simultaneously. Emergency response capabilities (effectiveness 4.6/5.0) prove critical for managing incidents inevitable despite prevention efforts—essential safety net protecting both infrastructure and workers when extreme events exceed prevention capacities.

Table 4. Archipelagic Port Network Vulnerability and Resilience Analysis.

Network Component	**Interconnection Role**	**Climate Vulnerability**	**Failure Cascade Impacts**	**Resilience Priority*********	**Adaptation Approaches**
Major Hub Ports (Tanjung Priok, Tanjung Perak, Makassar)	National gateway handling 60-70% of cargo	Very High - concentrated exposure	Critical - nationwide supply disruption	Critical (5.0/5.0)	Comprehensive adaptation, redundancy development
Regional Distribution Ports	Inter-island connectivity, regional supply chains	High - diverse geographic risks	High - regional isolation, shortages	Very High (4.6/5.0)	Distributed resilience, alternative routing
Specialized Cargo Facilities	Bulk, liquid, container terminals	Moderate-High - cargo-specific risks	Moderate-High - specialized supply disruption	High (4.3/5.0)	Specialized protection, alternative capacity
Coastal Community Ports	Remote access, essential services	Very High - limited resources	High - community isolation, humanitarian crisis	High (4.4/5.0)	Basic resilience, evacuation capability
Inter-Island Ferry Terminals	Passenger connectivity, vehicle transport	High - weather-dependent operations	High - population mobility disruption	High (4.2/5.0)	Weather protection, alternative transport
Naval and Government Facilities	Security, disaster response capacity	Moderate-High - strategic importance	High - security/response capability loss	Very High (4.7/5.0)	Priority hardening, operational continuity
Supporting Infrastructure (roads, rail, power)	Landside connectivity enabling port function	Very High - climate-sensitive linkages	Critical - port isolation despite facility function	Critical (5.0/5.0)	Integrated infrastructure adaptation
Information and Communication Systems	Coordination, tracking, logistics management	Moderate - technology resilience	High - operational coordination breakdown	High (4.5/5.0)	Redundant systems, cloud infrastructure

*******Resilience priority: 1=low priority, 5=critical national importance

Network vulnerability analysis demonstrates that major hub ports and supporting infrastructure both receive critical resilience priority (5.0/5.0) reflecting that port facilities alone prove insufficient without functioning road/rail/power connections—integrated infrastructure approach required rather than port-only adaptation focus. The failure cascade impacts rated "critical" or "high" across all network components validate that Indonesian archipelagic geography creates systemic vulnerabilities where single-point failures generate nationwide consequences—network resilience requiring coordinated adaptation across multiple infrastructure systems and geographic locations. Coastal community ports showing very high climate vulnerability (limited resources, concentrated exposure) yet high cascade impacts (community isolation, humanitarian crisis) demonstrate environmental justice dimension where most vulnerable populations face greatest climate risks—equity imperative ensuring adaptation protects vulnerable communities not only economically-strategic major facilities.

Table 5. Investment Requirements and Economic Analysis.

Investment Category	Capital Requirements	Annual Operating Costs	Benefit-Cost Ratio	Funding Sources	Implementation Urgency
Flooding Infrastructure (seawalls, drainage, elevation)	$800M-1.5B per major port	$15-30M maintenance	2.5-4.0:1	Government, port revenues, development banks	Critical - immediate implementation
Heat Protection Programs (cooling, training, equipment)	$15-35M per major port	$3-8M ongoing	4.0-6.5:1	Port operators, government occupational health, insurance incentives	Critical - worker safety emergency
Climate-Adapted Equipment	$100-250M equipment upgrades	$10-20M enhanced maintenance	2.0-3.5:1	Port operators, equipment leasing, vendor financing	High - equipment lifecycle planning
Nature-Based Solutions (mangroves, wetlands, reefs)	$25-60M per major coastal area	$2-5M stewardship	5.0-8.0:1	Environmental funds, development assistance, community programs	High - co-benefit optimization
Emergency Response Systems	$10-25M capacity building	$3-7M operations	3.0-5.0:1	Disaster management budgets, insurance, mutual aid	High - preparedness essential
Network Resilience Coordination	$50-100M planning and integration	$8-15M coordination	3.5-6.0:1	National infrastructure funds, regional cooperation	Very High - systemic protection
Worker Health Surveillance	$5-15M system establishment	$2-4M monitoring	6.0-10.0:1	Occupational health budgets, research funding	High - early intervention value
Climate Information Systems	$15-30M development	$3-6M updates	4.0-7.0:1	Science budgets, international cooperation	High - decision support critical

Investment analysis reveals that flooding infrastructure requires largest capital commitments ($800M-1.5B per major port) yet generates solid 2.5-4.0:1 benefit-cost ratios justifying substantial investments—economic viability supporting climate adaptation as financially-sound rather than purely defensive spending. Heat protection programs showing 4.0-6.5:1 benefit-cost ratios with relatively modest capital requirements ($15-35M) represent high-value investments addressing urgent worker safety while generating economic returns through productivity improvement and health cost avoidance—compelling business case for immediate implementation. Nature-based solutions offering exceptional 5.0-8.0:1 benefit-cost ratios demonstrate that ecosystem-based approaches provide cost-effective adaptation with substantial co-benefits—economic efficiency argument for prioritizing nature-based approaches where feasible alongside traditional engineering. Worker health surveillance showing highest benefit-cost ratio (6.0-10.0:1) with minimal capital requirements validates that early intervention preventing chronic disease proves far more cost-effective than treating established conditions—prevention investment logic supporting proactive occupational health programs.

Table 6. Implementation Barriers and Enabling Strategies.

Barrier Category	Specific Challenges	Severity Rating********	Mitigation Strategies	Success Indicators	Timeline
Immediate Infrastructure Damage	Already experiencing 3-8 flooding shutdowns, repairs needed now	Critical (4.9/5.0)	Emergency repairs, interim protection, accelerated planning	Damage reduction, disruption decrease	Immediate - ongoing
Investment Decision Window	$15-25B commitments 2024-2030, designs finalizing now	Critical (5.0/5.0)	Climate-informed design standards, mandatory resilience assessment	Adapted infrastructure specifications	12-24 months - closing rapidly
Fragmented Governance	Multiple agencies, unclear coordination, competing priorities	Very High (4.6/5.0)	Coordination mechanisms, clear accountability, integrated planning	Joint decision-making, aligned budgets	18-36 months institutional development
Technical Capacity Limitations	Limited climate adaptation expertise, engineering gaps	High (4.3/5.0)	Capacity building, international partnerships, technical assistance	Expert availability, quality improvements	24-48 months sustained development
Financial Resource Constraints	Competing demands, limited budgets, high costs	Very High (4.7/5.0)	Blended financing, international assistance, public-private partnerships	Secured funding, leveraged resources	12-24 months per project
Community Displacement Risks	Adaptation may force relocation, livelihood disruption	High (4.4/5.0)	Just transition planning, community participation, alternative livelihoods	No involuntary displacement, benefit sharing	24-48 months community engagement
Climate Uncertainty	Deep uncertainty in projections, risk of maladaptation	Moderate-High (4.0/5.0)	Adaptive pathways, flexible design, monitoring triggers	Responsive adaptation, avoided lock-in	Ongoing - continuous learning
Regulatory and Standards Gaps	No climate-adapted design codes, unclear requirements	High (4.2/5.0)	Standards development, regulatory clarity, enforcement capacity	Updated regulations, compliance	24-36 months policy development

********Severity: 1=minor obstacle, 5=critical barrier

Implementation barrier analysis identifies investment decision window (severity 5.0/5.0) as most critical challenge reflecting that $15-25 billion infrastructure commitments currently in planning/early construction stages must incorporate climate adaptation now before designs finalize—narrow opportunity requiring immediate action. Immediate infrastructure damage (severity 4.9/5.0) creates urgent parallel need for emergency protection while longer-term adaptation progresses—dual-track approach addressing both immediate crisis and future resilience. Fragmented governance (severity 4.6/5.0) and financial resource constraints (4.7/5.0) represent major obstacles requiring innovative coordination mechanisms and blended financing approaches—institutional and financial innovation essential for overcoming organizational and resource barriers. Community displacement risks (severity 4.4/5.0) raise environmental justice concerns requiring just transition approaches ensuring adaptation protects rather than harms vulnerable populations—equity imperative preventing adaptation from creating new injustices while addressing climate threats.

Discussion

The research findings illuminate how climate change threatens Indonesian ports through converging infrastructure vulnerabilities and worker safety hazards requiring integrated adaptation frameworks treating ports as coupled human-infrastructure systems where physical resilience and workforce protection prove inseparable (Becker et al., 2013). The current impacts documentation showing 3-8 annual flooding shutdowns (12-48 hours each, $15-35 million losses, adaptation 1.7/5.0) and 150+ worker heat illness cases in 2023 (300% increase from 2018, severity 4.5/5.0, protection 1.6/5.0) validates that climate change represents immediate operational and humanitarian crisis not distant future concern—urgent adaptation imperative addressing current damages and worker injuries rather than merely preventing projected future impacts. The supply chain cascade effects generating $50-150 million indirect costs per major disruption (adaptation 1.5/5.0 grossly inadequate) demonstrate that port climate failures create nationwide economic consequences far exceeding direct facility damages—systemic vulnerability requiring network-level resilience approaches protecting Indonesia's archipelagic logistics system supporting 270 million population rather than isolated facility-by-facility adaptation (Lam et al., 2018).

The worker health impact analysis revealing acute heat illness epidemic (150+ cases, multiple fatalities, 300% increase) alongside chronic heat exposure affecting 30-45% of workforce with long-term kidney and cardiovascular disease validates that occupational climate adaptation proves as urgent as infrastructure protection, with workers facing immediate life-threatening hazards requiring emergency intervention—humanitarian imperative that worker safety deserves equivalent priority as physical asset protection rather than accepting worker exposure while investing billions protecting buildings and equipment (Kjellstrom et al., 2016). The projected future risk assessments indicating heat stress "approaching thermal limits" reflect that current severe conditions will intensify substantially as climate change progresses potentially making outdoor port work impossible during peak heat periods within 2-3 decades—existential threat to port operations requiring fundamental work redesign, technological solutions enabling remote/automated operations, or accepting seasonal operational constraints fundamentally reshaping maritime logistics in tropical regions. The universally inadequate worker protection measures (rated 1.4-2.3/5.0) compared to infrastructure adaptation responses (though also inadequate at 1.5-2.4/5.0) demonstrate systematic bias prioritizing physical asset protection over human safety—organizational value system requiring transformation recognizing that operations depend equally on functioning infrastructure and protected healthy workforce (Messner et al., 2013).

The integrated adaptation framework revealing that flooding protection (effectiveness 4.7/5.0), climate-adapted infrastructure design (4.8/5.0), and emergency response capabilities (4.6/5.0) constitute highest-impact interventions demonstrates that fundamental infrastructure adaptation addressing primary climate vulnerabilities generates greatest resilience improvements, though requiring high-to-very-high implementation complexity and substantial sustained investment—realistic assessment of adaptation scale and costs rather than suggesting simple solutions (Nicholls et al., 2008). Heat stress management programs showing high effectiveness (4.4/5.0) with moderate-high complexity represent practical high-value worker protection intervention addressing urgent occupational safety needs while generating productivity co-benefits through reduced heat-related performance degradation—compelling business case supporting worker safety investment as operational enhancement not merely humanitarian expense. Nature-based solutions achieving high effectiveness (4.2/5.0) with exceptional benefit-cost ratios (5.0-8.0:1) validate that ecosystem-based approaches provide cost-effective adaptation with substantial co-benefits including biodiversity protection, carbon sequestration, fisheries support, and community employment—multi-benefit optimization supporting nature-based solutions as complementary approaches alongside traditional engineering rather than either-or choices (Becker et al., 2013).

The archipelagic network vulnerability analysis demonstrating that major hub ports and supporting infrastructure both receive critical resilience priority (5.0/5.0) reflects that port facilities prove insufficient without functioning landside connections—integrated infrastructure approach required addressing roads, rail, power, and water systems enabling port operations rather than port-only adaptation leaving facilities operational but inaccessible or non-functional due to supporting infrastructure failures (Lam et al., 2018). The network failure cascade impacts rated "critical" or "high" across all components validate that Indonesian archipelagic geography creates systemic vulnerabilities where single-point failures generate nationwide consequences—coordination challenge requiring network-level strategic planning identifying critical nodes, developing redundancy, and ensuring that adaptation investments protect integrated logistics system rather than creating fragmented resilient facilities within fragile networks. Coastal community ports showing very high climate vulnerability yet high cascade impacts demonstrate environmental justice dimension where most vulnerable populations face greatest climate risks—equity imperative ensuring adaptation protects vulnerable communities and addresses disproportionate impacts rather than concentrating resources on economically-strategic major facilities while neglecting small ports serving marginalized populations (Messner et al., 2013).

The investment analysis revealing flooding infrastructure requires $800M-1.5B per major port yet generates 2.5-4.0:1 benefit-cost ratios demonstrates that climate adaptation constitutes financially-sound investment not merely defensive spending—economic viability supporting substantial resource allocation to adaptation as economically-rational protecting high-value assets and economic activity rather than accepting climate damages (Nicholls et al., 2008). Heat protection programs showing 4.0-6.5:1 benefit-cost ratios with modest capital requirements ($15-35M) represent exceptional value investments addressing urgent worker safety while generating economic returns—compelling business case enabling rapid implementation without requiring massive financial mobilization. Nature-based solutions' exceptional benefit-cost ratios (5.0-8.0:1) validate economic efficiency of ecosystem approaches—pragmatic economic argument for nature-based solutions alongside environmental sustainability rationales often dismissed by financially-conservative port operators and government officials. Worker health surveillance showing highest benefit-cost ratio (6.0-10.0:1) demonstrates that prevention through early intervention proves far more cost-effective than treating established chronic diseases—public health investment logic supporting proactive occupational health programs as economically-optimal strategies (Kjellstrom et al., 2016).

The implementation barriers identifying investment decision window (severity 5.0/5.0) as most critical challenge reflects that current $15-25 billion infrastructure planning and early construction must incorporate climate adaptation immediately before designs finalize and construction begins locking in vulnerable infrastructure—narrow opportunity measured in months not years requiring urgent mobilization of climate adaptation frameworks informing current investment decisions. Immediate infrastructure damage (severity 4.9/5.0) creates parallel emergency requiring interim protection while longer-term adaptation progresses—dual-track approach addressing both urgent crisis management and sustained adaptation implementation rather than sequential approach delaying adaptation until emergency repairs complete. Fragmented governance (severity 4.6/5.0) across multiple agencies including Ministry of Transportation, Ministry of Environment, Ministry of Public Works, provincial authorities, and port operators requires innovative coordination mechanisms creating integrated decision-making—institutional challenge potentially more difficult than technical engineering yet essential for effective implementation (Lam et al., 2018). Community displacement risks (severity 4.4/5.0) requiring just transition approaches demonstrate that adaptation planning must explicitly address social equity ensuring vulnerable coastal populations benefit from rather than suffer from adaptation investments—procedural and distributive justice imperatives preventing adaptation from creating new injustices while addressing climate threats (Becker et al., 2013).

This research contributes to port climate adaptation literature by demonstrating that effective approaches require integrated frameworks treating ports as coupled human-infrastructure systems where physical resilience and workforce protection prove inseparable—holistic perspective contrasting with infrastructure-centric approaches dominating current practice and literature. The Indonesian archipelagic focus provides insights into network vulnerabilities and cascade effects characteristic of island nations yet underrepresented in adaptation literature predominantly examining continental ports—transferable knowledge for Philippines, Pacific Islands, Caribbean nations, and other archipelagic contexts sharing similar geographic characteristics. The worker safety emphasis addresses critical gap where occupational climate adaptation receives minimal attention despite workers facing immediate severe health hazards—human rights and environmental justice contribution recognizing that climate adaptation must protect people not only property. The investment urgency documentation provides compelling argument for immediate action given narrow decision windows—practical policy relevance supporting adaptation mainstreaming into current infrastructure planning rather than treating adaptation as future concern.

4. Conclusion

This research demonstrates that Indonesian ports face existential climate threats through converging infrastructure vulnerabilities and worker safety hazards requiring integrated adaptation frameworks treating ports as coupled human-infrastructure systems. Current impacts including 3-8 annual flooding shutdowns causing $15-35 million losses and worker heat illness epidemic (150+ cases in 2023, 300% increase, multiple fatalities) validate immediate crisis demanding urgent intervention not future planning. Comprehensive adaptation frameworks integrating flooding protection, heat stress management, climate-adapted infrastructure design, emergency response capabilities, and nature-based solutions can reduce operational disruptions by 50-70%, decrease worker heat illness by 60-80%, and enhance infrastructure resilience by 45-65% while generating compelling 2.5-8.0:1 benefit-cost ratios. Implementation requires addressing critical barriers including investment decision urgency ($15-25B commitments 2024-2030 requiring immediate climate integration), fragmented governance, resource constraints, and community displacement risks through coordinated strategies, blended financing, and just transition mechanisms. Findings establish that successful climate adaptation demands holistic sociotechnical approaches addressing infrastructure resilience, workforce protection, network vulnerabilities, and social equity through sustained multi-stakeholder coordination supporting Indonesia's maritime economic security and coastal community welfare.

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